WATER QUALITY MONITORING IN WATER SUPPLY SYSTEMS: AN INTEGRATED APPROACH

[1]Yiannis A. Papadimitrakis and [2]Angelos N. Findikakis

[1] National Technical University of Athens, School of Civil Engineering Hydraulics, Water Resources and Maritime Engineering Division, Iroon Polytechniou 9, Zografos Campus,
15780 Athens, GREECE
[2] Bechtel National Inc., 50 Beale Street, San Francisco, California 94105, USA

Biographical Sketches of Authors
Professor Ioannis (or Yiannis) Papadimitrakis is a faculty member of the School of Civil Engineering of the National Technical University of Athens (NTUA), in Athens Greece.

He has done research work on a variety of issues in the broader areas of Environmental Fluid Mechanics-Hydraulics and of Marine Hydrodynamics.

He, along with other colleagues from Chemical and Electrical Engineering of NTUA and from abroad, is promoting the ideas of proper design and operation of advanced remotely operating systems for monitoring the quality of (drinking) water in distribution networks (inside cities), in fresh water Reservoirs, and in aqueducts supplying water to treatment facilities.

He received a Diploma in Civil Engineering from the National Technical University of Athens in Greece, two MSc Degrees from Stanford University (one in Water Resource Engineering from Civil Engineering and one in Fluid Mechanics from Mechanical Engineering), and a joint Ph.D form Civil and Mechanical Engineering Departments of Stanford University.

He is the author of numerous Journal and Conference Papers and serves as a reviewer in various Journals.

Dr. Angelos Findikakis is a Senior Principal Engineer with Bechtel National in San Francisco. He is also a Bechtel Fellow, which is the highest Bechtel honor in recognition of technical excellence. As a Bechtel Fellow he acts as Bechtel's technical ambassador and as a special technical advisor to upper management.

He has worked on a variety of environmental and water resources studies, including both surface and ground water problems. Examples of his recent assignments in Bechtel are the study of the National Water Plan for Morocco, the integral study for the environmental remediation of Lake Maracaibo in Venezuela, and the thermal analysis of the Russian Fissile Material Storage Facility. He is currently working on the Yucca Mountain project.

He received his Diploma in Civil Engineering from the National Technical University of Athens, Greece, and his MSc in Water Resources Planning and PhD in Civil Engineering from Stanford University. His doctoral dissertation was on environmental fluid mechanics.

He is also a Consulting Professor in the Department of Civil and Environmental Engineering at Stanford University.

He is the author of several journal and conference papers. He has received different awards including the Straub Award, the ASCE Hering Medal, and the ASCE Horner Award. He is a member of many national and international organizations, societies and committees, including ASCE, AGU, IAHR and Sigma Xi and has served in several professional organization committees.

Abstract
The use of state-of-the-art technology allows the continuous, automated and telemetric monitoring of different physical and chemical parameters that characterize water quality in water supply systems (reservoirs and aqueducts), with simultaneous monitoring of water flows driven by the external forces affecting reservoir circulation, including wind, heat transfer due to solar and atmospheric radiation, incoming river discharges,

water withdrawal, etc. This can be achieved by combining *in situ* automated sensors installed in the reservoirs, the incoming river and at selected locations along the aqueducts from the reservoir to the respective treatment facility, with software that simulates, in real time, the reservoir hydrodynamics, aqueduct hydraulics and water quality of the entire reservoir and aqueduct system, utilizing actual time series of the monitored parameters through a data assimilation scheme. This paper describes the possibilities offered by currently available technology for integrated water quality monitoring in reservoirs and open aqueducts and discusses the system envisioned for the major reservoirs and aqueducts of the water supply system of the Athens metropolitan area.

1. INTRODUCTION

The European Union (EU) has recognized the need for both the development of surface water monitoring programs in every watershed (article 8 of the EU Directive 2000/60, issued on 10.23.2000) and the adoption of special pollution prevention measures to protect surface water resources, especially in places where various pollutants pose a risk to human health (article 16 of the same directive). Measures to prevent contamination from these pollutants should aim at their gradual reduction, and for the most hazardous ones, at their eventual elimination.

Regular monitoring of the physical, chemical and biological parameters characterizing water quality is essential for assessing the state of an aquatic ecosystem. The data collected from such monitoring: a) allow the early detection of changes and trends in water quality, b) provide the basis for the calibration of predictive water quality and ecological models, c) allow evaluation of alternative remediation strategies, and d) contribute to the advancement of the fundamental understanding of the behavior of these water bodies.

During the last two decades there has been a dramatic increase in the use of numerical simulation models for both coastal and inland water bodies. These models often focus on the prediction of production, transport, chemical and biological transformations and the impact, on the aquatic environment, of various pollutants. Hydrodynamic, water quality and ecological models are used interdependently to predict the impact of the presence and/or further disposal of nutrients, or other pollutants on the aquatic ecosystem. The major weakness of most simulation models is the lack of sufficient validation with field data, especially during critical short duration events, making thus many numerical simulations mere academic exercises.

Even though mathematical models are capable of predicting the water quality conditions on a continuous basis, thus providing relevant information among sparsely collected observations in either space or time, and describing the field dynamics, they are rarely used as interpolation tools. A properly designed interpolation process could lead to a significant reduction of the volume of recorded data and more strategic placement of the instrumentation used in locations where the spatial and temporal variability of the monitored parameters is higher and of a greater importance in terms of assessing the state of the water enclosure in question.

Conventional measurements of parameters that characterize the water quality of inland waters, through sample collection and analysis, are made quite regularly today in both lakes and rivers. Disadvantages of the conventional monitoring methods are: a) the small number of samples that are collected, giving a relatively limited coverage of the spatial (horizontal and vertical) distribution of the measured parameters, b) the low frequency and sometimes the aperiodic nature of such measurements, c) often the absence of simultaneous monitoring of external forcing parameters (wind, solar radiation, inflows and outflows, etc) and of the generated flow field which, not only affects, but possibly determines water quality, d) the high cost.

The dynamic nature of enclosed water bodies due to water circulation resulting from various external forces, but also due to the simultaneous transport and transformation of the various substances found in them, is the main cause of the variability of the physical, chemical, and biological processes (and parameters) which define water quality. Therefore, water samples from a small number of specific locations at a particular time may not necessarily be representative of water quality in the reservoir before, or after that time. This conventional monitoring philosophy must give way to more recent monitoring concepts, such as those used successfully in meteorological and oceanographic studies. Integrated water quality monitoring systems are today commercially available and have been used in the ocean, lakes and rivers [1,2]. A similar monitoring system has also been proposed, by the first author, for operational use in water distribution systems covering the needs of smaller and/or larger cities [3,4].

It is noted though that systems of automated continuous recording of hydrodynamic and water quality parameters have been installed and operate in several rivers in Greece, e.g. the system REMOS that monitors several environmental quality parameters in the river Nestos, in northern Greece, and the Lake "Agiasma" located at the delta of Nestos. The Public Power Corporation (PPC) of Greece has installed a monitoring station recording a limited number of water quality parameters in the reservoir of "Thesauros", and is planning to install similar systems in other reservoirs. An extensive monitoring system will be installed at the "Amvrakikos" Gulf, a shallow lake that communicates with the open sea. Another monitoring system, the system POSEIDON, operates in the Aegean Sea [5].

The last few years a systematic effort has been underway to address the need for improved and affordable management of different water bodies, by developing integrated systems for monitoring, simulating and managing reservoirs and the associated water supply networks used to convey water from the reservoirs to the respective treatment plants. Such systems include instruments of automated, continuous recording of the measured parameters, and software that allows the user to collect, use, present and archive environmental data, with the aid of a Geographic Information System (GIS) and other data management tools. In addition, a typical system of this type uses special software to simulate the hydrodynamic behavior of the water body, as well as the transport and transformation of various potential pollutants, in order to predict the overall water quality and ecosystem health, utilizing real time data with the aid of a data assimilation scheme. This paper describes the system envisioned for the water supply system that serves the metropolitan area of Athens. The system consists of four reservoirs shown in Figure 1, namely: Evinos with a storage capacity of 112 Mm^3, Mornos (630 Mm^3), Yliki (585 Mm^3), and Marathon (31 Mm^3). The reservoirs are connected by nearly 200 (=150 + 50) km of open aqueducts; 150 km belong to the Mornos water supply system, and the remaining 50 km belong to the Yliki aqueducts.

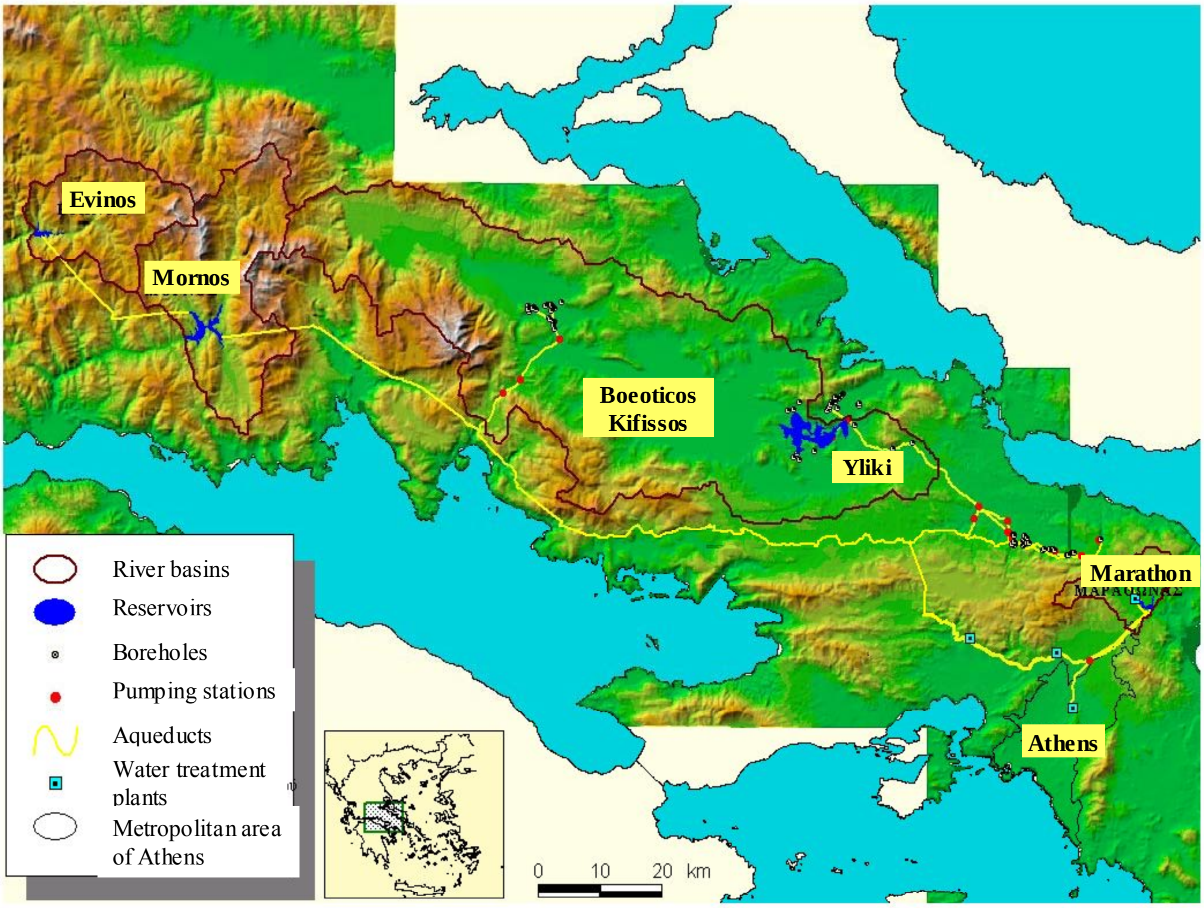

Figure 1. The major reservoirs and aqueducts of the Athens water supply system.

2. THE RESERVOIR MONITORING SYSTEM

The water quality monitoring system envisioned for the four reservoirs and the corresponding supply aqueducts, which serve the needs of the Athens metropolitan area, will consist of two parts: 1) a system of continuous automated, telemetric recording of water quality and other parameters that affect water quality, e.g. meteorologic and hydrologic data, and 2) a software for the simulation of the recorded water quality, and other not directly recorded, parameters.

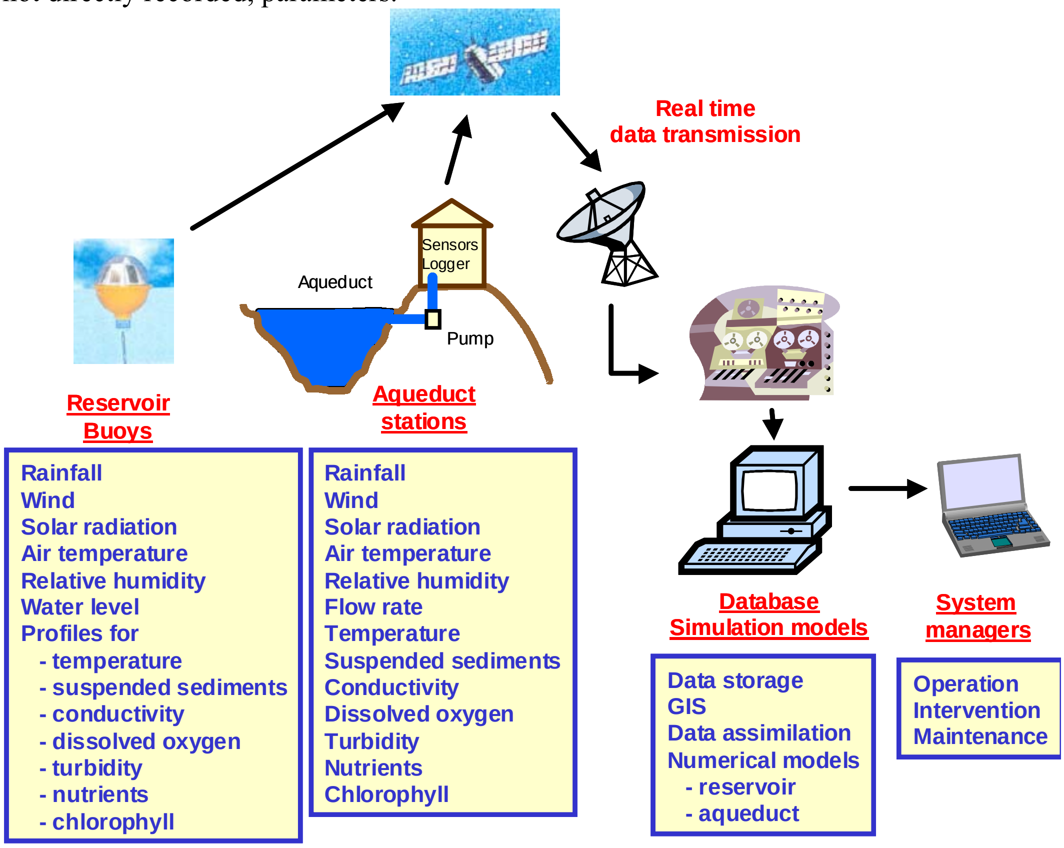

Figure 2. Illustration of the monitoring/modeling concept envisioned for the reservoirs and aqueducts of the Athens water supply system.

The system of automated, continuous, telemetric monitoring typically will consist of one or more buoys anchored at selected stations in the reservoir, properly equipped with a small mast and instrumented for monitoring basic meteorologic data, (e.g. wind speed and direction, atmospheric pressure, air temperature, relative humidity and solar radiation), water level, water temperature and salinity/conductivity, pH, turbidity, dissolved oxygen, nitrates and nitrites, phosphates, total phosphorus, orthophosphates, light extinction with depth, heavy metals, and chlorophyll a. If deemed necessary, it is possible to add to the monitoring system analytical instrumentation for determining the chemical oxygen demand (COD) and total organic carbon (TOC), total bacteria and coliforms, as well as instrumentation for radioactivity.

The monitoring system will include also, at least, one station to monitor water quality in the main river flowing into each reservoir. This station will have instrumentation for recording the river stage, water temperature, salinity/conductivity, pH, redox potential, dissolved oxygen, nitrates and nitrites, phosphates, total phosphorus, orthophosphates, COD and TOC, total bacteria and coliforms.

A typical reservoir simulation model consists of at least two modules, a hydrodynamic and a water quality module. The first simulates hydrodynamic circulation in the reservoir using as input inflow (direct runoff and streamflows, including controlled releases from upstream reservoirs) and outflow data, and data on external forcing, such as wind and meteorological parameters that control the heating or cooling of the reservoir. The dimensionality and complexity of the hydrodynamic module depends on the size, geometry and other special characteristics of the reservoir. For some reservoirs, a one-dimensional, in the vertical, model can adequately reproduce the annual cycle of stratification and with the use of special formulations the model can account for the effect of variable temperature inflows, density currents, thermal stratification, selective withdrawal, etc. The Evinos reservoir of the Athens water supply system has a relatively simple geometry extending upstream of the dam along the Evinos river and falls in this category (see Figure 3). In some cases though, such as for example the reservoir of Mornos (see Figure 3), the geometry of the reservoir may be quite complex with multiple arms receiving the water of different tributaries that a two-dimensional, or a three-dimensional model is justified.

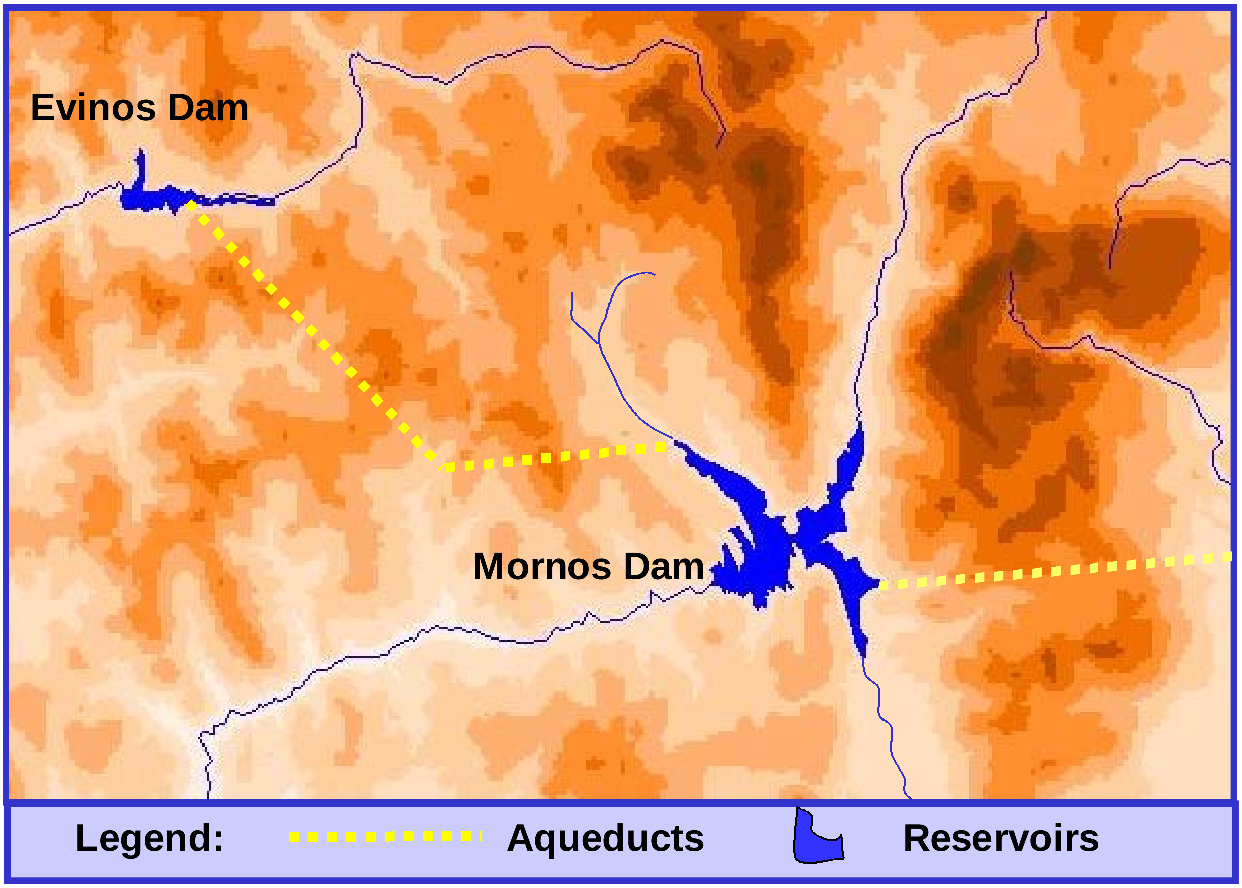

Figure 3. Two of the reservoirs of the water supply system of the metropolitan area of Athens: Evinos and Mornos.

The water quality module solves the mass conservation equation for different compounds and parameters of concern, e.g. nutrients, heavy metals, suspended sediments and pathogens, accounting for chemical reactions where needed. It predicts the transport and transformation of the simulated water quality parameters through the simulation of the nitrogen and phosphorus cycles, the phytoplankton kinetics and dissolved oxygen budget, accounting for their interaction with the suspended and bottom sediments. The water quality module may also account for other biological and ecological parameters, like bacteria (total and coliforms), phytoplankton (through the simulation of chlorophyll a or other relative indicators), zooplankton, etc. The water quality module is linked with the hydrodynamic module, by using the velocity and temperature fields produced by the hydrodynamic module, to simulate the transport of different chemical and biological parameters.

The mathematical model of each of the four reservoirs of the Athens water supply system will be developed in steps. First, the hydrodynamic module will be tested independently of the water quality module by checking its ability to reproduce well the annual stratification cycle and other hydrodynamic characteristics of the reservoir. The next step will involve the development of the water quality module, testing first its ability to simulate the variability of dissolved oxygen (DO), different forms of nitrogen (N), phosphorus (P) and chlorophyll a, and in a later stage the incorporation of zooplankton and other parameters, e.g. heavy metals. The hydrodynamic and the water quality modules will have interfaces with appropriate data input and data processing modules, and/or with a geographic information system.

The two main modules of the reservoir simulation model will use the data recorded by the instrumentation on the buoy and the on-land station through a scheme of data assimilation, to optimize the performance of the mathematical models in terms of their ability to simulate the parameters in question over the entire simulation field. The data assimilation system may include different schemes for the hydrodynamic module and the water quality module, given the different nature of the equations in each of these two modules.

It is envisioned that the installation of the monitoring system in the reservoirs will be preceded by:

a) a systematic compilation, analysis and evaluation of all existing data, as well as an effort to organize and store these data in a database. This database will include data for each reservoir and its drainage basin, e.g. meteorological, hydrologic and water quality data, as well as information on actual or potential pollution sources in its watershed. This information will be used subsequently to estimate the pollution load that enters the reservoir, which will be input to the water quality model.

b) a water quality data collection program using conventional methods. This will include data collection at different locations and reservoir depths (and at the inflowing rivers), during both the dry season, especially during the period of thermal stratification, and the wet season These data will provide an initial picture of water quality in the reservoir which will support the development of the model, and will help design the continuous monitoring program, by facilitating the final selection of the sensors that must be purchased and installed.

3. MONITORING SYSTEMS FOR AQUEDUCTS

A similar integrated water quality monitoring system is envisioned at selected locations along the open portion of the supply aqueducts of the system, from the Evinos, Mornos, Yliki and Marathon reservoirs to the respective treatment facilities around the Athens metropolitan area. The measuring system for the open aqueducts will be similar to that for monitoring water quality in the rivers flowing into the reservoirs, i.e. it will be installed on land. At each station there will be a computer with different (monitoring) sensors and the corresponding transducers, and other electronic signal processing devices, such as amplifiers, filters, etc. The location of the monitoring stations will be selected based on careful examination of the variability of different water quality indicators along the length of the aqueduct, and to a lesser extent based on secondary criteria, such as the topography of the area. The examination of water quality variability along the aqueducts will be made initially, before the installation of the permanent monitoring stations, with conventional means during both the period of high water supply, e.g. in the summer, and during the rain season, taking into account the hydraulic characteristics of the open part of the aqueduct and the supplied flow rates. An effort will be made to determine to what extent the variability of the water quality is due to changes in the hydraulic characteristics of the aqueduct (friction, cross sectional geometry), and to what extent is due to local changes in the flow rate, or other factors, e.g. the local presence of algae.

In a typical monitoring station, along the aqueduct, water will be diverted either naturally or with the aid of a small pump in an adjacent sump, to the side of the aqueduct, for in situ sampling and analysis. A computer with different sensors and devices will be placed at an adjacent portable container and the corresponding information will be either recorded locally on this computer, or it will be transmitted electronically to a central data collection and evaluation center.

A computer model will also be used to predict water quality along the length of each aqueduct. This model will be much simpler than its counterpart for the reservoir, because of the much simpler hydraulics, transport and transformation processes that affect the fate of pollutants and other substances in open aqueducts compared with those in reservoirs.

An important function of the monitoring system will be to provide early warning in the event that water quality in the aqueduct is threatened by natural hazards, and intentional or accidental human activities. As key infrastructure elements of the water supply systems of major metropolitan areas, it is conceivable that open aqueducts, and to a lesser extent reservoirs, may become in the future the target of terrorist activities. In order to improve the security of an open aqueduct one must first assess its vulnerability to activities, such as the introduction of toxic chemical or biological agents in the water.

The vulnerability assessment of an aqueduct to physical disasters and other threats should aim at determining ways that would help the responsible water agencies protect public health, as quickly and effectively as possible, by minimizing the anticipated risks and by providing early warning if such an event happens. This assessment must be comprehensive and should address several specific issues, e.g. the probability of occurrence of specific threats to the aqueduct (and/or reservoir), overlooked aspects of physical protection of the system, ways to minimize the impact of potential physical disasters, new potential threats in view of various international crises (terrorism), available protection systems and technologies for reservoirs, aqueducts and water treatment facilities, differences in the response to natural disasters and terrorist activities, etc.

There are different methods for the detection of the presence of undesirable (chemical and biological) substances in open aqueducts. Besides continuous sampling and analysis using standard chemical methods, other methods and techniques based on monitoring the behavior of the immune system of different organisms can be used. For example, an indicator of the presence of toxic substances in the water can be based on the response of microorganisms with fluorescent properties, such as special fish (cyprinidae, e.g. carp), daphnia, copepods, etc, which are sensitive to these substances. Monitoring the state of the health of these organisms requires sensitive sensors and advanced techniques of optical imaging (which are combined with an appropriate computer model and response protocols of the monitored organisms), as well as other laboratory analyses. This methodology of biological monitoring of the aqueduct can be effective only in combination with the appropriate instrumentation and computer model, which of course can be part of an integrated water quality system.

4. CONCLUSIONS

The described monitoring system is viewed as an important element of an integrated approach for monitoring, simulating and managing water quality in reservoirs, water supply aqueducts and other water enclosures. This system aims at providing the user with means for quick and efficient environmental data collection, analysis, presentation/visualization and storage of the results. It is capable of simulating the most important physical, chemical, and biological processes and their interaction. This capability is used with real time data and predictions of the environmental state of the water enclosure in the entire monitored area.

Such a system will meet the requirements of EU regulations and will provide a viable option for monitoring and managing water quality in reservoirs and supply aqueducts. Despite its impressive advantages, it has not yet been established internationally, but all indications are that its establishment is a matter of time. In Greece, besides the systems of limited monitoring capabilities, mentioned in the introduction, no such complete system is in use. The Greek Water Supply Company for the Athens metropolitan area (EYDAP), following a recommendation of the first author, has accepted in principle its value, and intends to soon install it in the reservoirs operating under its control. Similar systems have been installed in the European Union (e.g. in Norway and elsewhere), as well as in Poland. These systems, though, are not as comprehensive as the system described in this paper.

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